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A SIMULATED REDUCTION IN ANTARCTIC SEA-ICE AREA SINCE 1750: IMPLICATIONS OF THE LONG MEMORY OF THE OCEAN

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ABSTRACT

Using the three-dimensional coarse-resolution climate model ECBILT-CLIO, 1000-year long ensemble simulations with natural and anthropogenic forcings have been performed to study the long-term variation of the ice cover in the Southern Ocean. Over the last 250 years, the ice area has decreased by about 1×10^6 km^2 in its annual mean. A comparison with experiments driven by only natural forcings suggests that this reduction is due to both natural and anthropogenic forcing, the latter playing a larger role than natural forcing over the last 150 years. Despite this contribution from anthropogenic forcing, the simulated ice area at the end of the 20th century is similar to that simulated during the 14th century because of the slow response of the Southern Ocean to radiative forcing. Sensitivity experiments performed with the model show that the model's initial conditions have a large influence on the simulated ice cover and that it is necessary to start simulations at least two centuries before the period of interest in order to remove this influence. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: sea ice; Southern Ocean; climate change; ice extent trends; climate modelling

1. INTRODUCTION

Over the period 1978–2002, the ice extent in the Northern Hemisphere derived from satellite records has decreased at a rate of about 0.3×10^6 km^2 per decade (e.g. Parkinson *et al*., 1999; Cavalieri *et al*., 2003). A significant part of this decrease has been attributed to the increase in the greenhouse gas concentration in the atmosphere since the beginning of the industrial era (e.g. Vinnikov *et al*., 1999; Houghton *et al*., 2001; Johannessen *et al*., 2004). In contrast, the ice extent in the Southern Hemisphere has increased by more than 0.2×10^6 km^2 over the same period (e.g. Watkins and Simmonds, 2000; Zwally *et al*., 2002; Cavalieri *et al*., 2003).

By using early satellite data covering the period 1972–77 and National Ice Center (NIC) digital sea-ice data set in order to bridge the gaps with the more recent satellite records, Cavalieri *et al*. (2003) suggest a decrease of the Antarctic ice extent by almost 2×10^6 km^2 between 1973 and 1977. This leads to a decreasing trend of 0.15×10^6 km^2/10 years over the period 1972–2002. The large decrease in the 1970s responsible for this trend, which was probably preceded by an increase from 1968 to 1973 (Zwally *et al*., 1983; Cavalieri *et al*., 2003), has also been obtained in a simulation using a coupled ice–ocean model driven by the National Centers for Environmental Prediction–National Center for Atmosphere Research reanalysis, but with a smaller magnitude (Fichefet *et al*., 2003).

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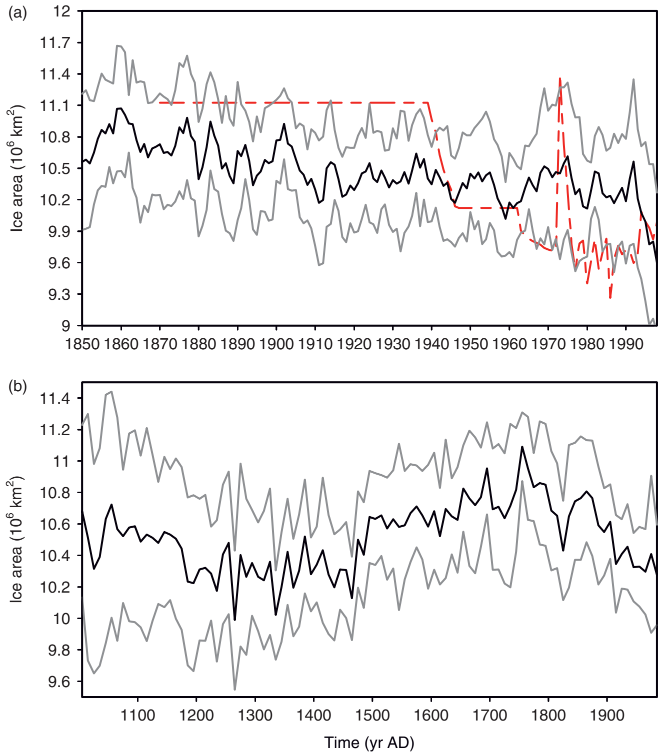

Figure 1. (a) Annual mean ice area in the Southern Hemisphere during the last 150 years averaged over 10 simulations that differ only in their initial conditions (black solid). The mean over the ensemble plus one and minus one standard deviation of the ensemble are in grey. The dashed line represents the observed ice area compiled from various sources (HADISST1; Rayner *et al*., 2003). Before the 1970s, this time series does not include interannual variations, as it is based only on two climatologies. (b) Annual mean ice area in the Southern Hemisphere during the last 1000 years averaged over 10 simulations that differ only in their initial conditions (black solid). The mean over the ensemble plus one and minus one standard deviation of the ensemble are in grey. Before constructing (b), the data have been grouped in 10-year long averages. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

No satellite observations are available from the period before the end of the 1960s and the information about the ice extent in the Southern Hemisphere is thus fragmentary and/or indirect. In their time series of ice extent over the last 130 years (HADISST1), Rayner *et al*. (2003) used a German climatology covering the period 1929–39 and a Russian one covering the years 1947–62, both based on ship observations of the ice cover (for details see Rayner *et al*. (2003)). The ice extent in those climatologies exceeds present-day observed values by roughly 10% (Figure 1(a)). Nevertheless, because of the limited number of observations available for developing those German and Russian climatologies, Rayner *et al*. (2003) caution that their reconstruction provides only a general indication of sea-ice variations before the 1970s.

Early Antarctic voyages also provide information on the past location of the ice edge. In a compilation of the records from the expeditions of Cook, Bellingshausen, Wilkes and Ross in the late 18th and early 19th centuries, Parkinson (1990) found some evidence of a larger ice cover in summer during this period. However, those observations do not indicate major differences compared with satellite data obtained in the 1970s (Parkinson, 1990).

In a reconstruction of the ice extent from whaling records, de la Mare (1997) suggests a decline in summer ice extent of about 25% between the mid 1950s and the early 1970s. Unfortunately, the ability to reconstruct ice-edge location from whaling catch position has been challenged by various authors. In particular, Ackley *et al*. (2003) argue that there is some evidence for a larger ice extent in summer in the Weddell and Ross Seas during the 1950s but not for the 25% changes of the mean ice extent proposed by de la Mare (1997).

An alternative way to reconstruct the past variation of the sea-ice cover is to use the proxy information provided by ice cores. Using methanesulphonic acid (MSA) measured in the Law Dome ice core as a proxy for the maximum ice extent in the 80–140 °E sector, Curran *et al*. (2003) suggest a 20% decline since about 1950. Their MSA record is also weakly correlated with the total Antarctic sea-ice extent. Nevertheless, extrapolating information from a restricted area to the whole Southern Ocean must be made with great care (e.g. Watkins and Simmonds, 2000; Zwally *et al*., 2002).

This brief overview indicates that there is no accepted consensus on the long-term variation of the Antarctic ice extent. There are also large uncertainties on the past surface air temperatures recorded for Antarctica because of the limited spatial coverage of available data and of the short records of the majority of weather stations (e.g. Turner *et al*., 2004). Nevertheless, the surface air temperatures appear relatively stable during the last 25 years, with even cooling in some regions (e.g. Comiso, 2000; Doran *et al*., 2002; Turner *et al*., 2002), whereas longer records indicate generally colder temperatures at the beginning of the 20th century than during the last decades (e.g. Jones, 1990; Vaughan *et al*., 2003). This warming during the 20th century seems to be part of a longer term trend as the 17th, 18th and 19th century temperatures deduced from proxy records are generally lower than present-day values (e.g. Morgan, 1985; Stenni *et al*., 2002; Goosse *et al*., 2004).

The goal of this study is to gain insights into the causes of long-term variation of the Antarctic ice cover in the Southern Ocean using an ensemble of simulations performed with a three-dimensional climate model driven by the main natural and anthropogenic forcings and to compare modelled trends with observations and proxy evidence. We first focus on the last 150 years because this corresponds to the years during which the major anthropogenic perturbations occurred and to the years that have been the most extensively analysed, as discussed above. In a second step, the variation during the last 150 years will be put in the wider context of the variation during the last millennium.

Several studies (e.g. Stouffer *et al*., 1989; Manabe *et al*., 1991; Weaver *et al*., 2000; Goosse and Renssen, 2001; Bi *et al*., 2001) have shown that the response of the Southern Ocean to an increase in the concentration of greenhouse gases in the atmosphere is delayed or damped compared with other regions. This could be due firstly to the large heat capacity of the Southern Ocean; secondly to changes in the hydrological cycle that would affect the upward oceanic heat flux; and thirdly to changes in ocean heat transport and in the characteristics of the deep waters that upwell in the Southern Ocean.

On the other hand, the changes in the atmospheric circulation related to El Niño–southern oscillation (ENSO) or the southern annular mode (SAM) could also have an impact on the ice concentration (e.g. Kwok and Comiso, 2002; Liu *et al*., 2004). In particular, trends of those modes, such as the one observed for SAM during the last 20 years (e.g. Marshall, 2003), might have an impact on the long-term variation of the ice. Nevertheless, the longer term reconstructions of SAM do not display clear trends during the last 150 years (Jones and Widmann, 2003). Furthermore, the studies covering the last decades suggest that the impact of SAM and ENSO on the ice cover is mainly regional and could have different signs in different regions, leading to a weak and generally insignificant contribution when integrated over the whole Southern Ocean (e.g. Kwok and Comiso, 2002; Liu *et al*., 2004; Lefebvre *et al*., 2004). Nevertheless, those results should be taken with caution, and different conclusions might be drawn when longer time series become available.

It is thus useful to determine whether the simulated changes in ice concentration are consistent with the observed increase in greenhouse gas concentration, to a delayed response to a past (natural) forcing or to other factors. To do so, we have performed experiments in which the model is driven by natural forcing only and compared with experiments using both natural and anthropogenic forcing. The influence of the delayed response of the Southern Ocean on the design of numerical experiments is also examined, more particularly the choice of initial conditions. Indeed, because of the large computer time requirements of atmosphere–ocean general circulation models (AOGCMs), experiments aimed at the climates of the 20th and 21st centuries are often started in AD 1850 or even later. Given the lagged response of the Southern Ocean to forcings, initial conditions may still have a significant impact in the variation of the ice cover in the Southern Ocean during the 20th century. This impact is investigated here.

2. MODEL DESCRIPTION AND EXPERIMENTAL DESIGN

The atmospheric component of our coupled model is ECBILT2 (Opsteegh *et al*., 1998), a T21, three-level quasi-geostrophic model, with simple parameterizations for the diabatic heating due to radiative fluxes, the release of latent heat and the exchange of sensible heat with the surface. ECBILT2 is coupled to the CLIO model (Goosse and Fichefet, 1999) that is made up of a primitive equation, free surface ocean general circulation model coupled to a comprehensive thermodynamic–dynamic sea-ice model. The horizontal resolution of CLIO is 3° in latitude and longitude, and there are 20 unevenly spaced vertical levels in the ocean. The only flux correction in ECBILT–CLIO is an artificial reduction in the precipitation by 10% over the Atlantic and by 50% over the Arctic. The model sensitivity to a CO_2 doubling is 1.8 °C, which is in the low range of coupled atmosphere–sea-ice–ocean general circulation models.

Thanks to the relatively coarse resolution and the simplified parameterization used in the atmospheric model, the coupled model is one to two orders of magnitude faster than a state-of-the-art AOGCM. This allows the routine making of simulations covering one to several thousands of years or a large number of relatively long experiments. On the other hand, the model is not able to simulate realistically some phenomena that need high resolution in the atmosphere and/or the ocean, such as ENSO. More information about the model and a complete list of references is available at http://www.knmi.nl/onderzk/CKO/ecbilt-papers.html.

In the present study, we have performed ten 1000-long simulations over the period AD 1001–2000 using realistic forcings, these being the main natural (solar and volcanic) and anthropogenic forcings (increase in greenhouse gas concentrations and in sulphate aerosol load). The solar irradiance follows the reconstruction of Lean *et al*. (1995) extended back in time by Bard *et al*. (2000). The radiative forcing associated with volcanism is derived from Crowley (2000) and is included through changes in solar irradiance. The influence of sulphate aerosols is taken into account through a modification of surface albedo. The 10 simulations differ only in their initial conditions. Five of these initial conditions were taken from model states 250 years apart in a long control simulation using constant external forcings. The other ones were chosen from an experiment covering the last millenium but driven by natural (volcanic and solar) forcings only, each state selected being separated from the next one by 150 years.

In addition to those 10 standard experiments, five simulations were performed using natural forcing only. Those simulations differ from the standard ones only after AD 1750, since before that time anthropogenic forcing is assumed to be negligible. Finally, five experiments driven by both natural and anthropogenic forcings were started in 1850 in order to make a more straightforward comparison with the simulation performed with AOGCMs. In this case, the initial conditions are also taken from the model states 250 years apart in a long control simulation. The present study is focused on the Southern Ocean. The interested reader can find more information about the internal and forced variability of the model in the Northern Hemisphere and in particular in the Arctic in Goosse *et al*. (2002) and Goosse and Renssen (2003, 2004).

The model simulates reasonably well the climate variation in the Southern Hemisphere during the last millenium compared with available reconstructions (Goosse *et al*., 2004). Furthermore, the minimum of ice area (extent) in the Southern Ocean in summer averaged over the period 1975–2000 for the mean of the ensemble of simulations is 4×10^{12} m^2(5×10^{12} m^2) and the maximum in winter is 17×10^{12} m^2(20×10^{12} m^2), these being in good agreement with observations over that period (e.g. Zwally *et al*., 2002). Here, ice extent is computed as the total surface of the grid points with a concentration higher than 15%, and ice area is the total surface covered by ice (excluding, thus, the surface covered by leads). The following discussion is based on the analysis of the time series of ice area. Indeed, this variable is better conditioned for a coarse-resolution model, since a whole grid-point (3° × 3° in our case, see above) is included or excluded from the computation of ice extent whenever its concentration is higher/lower than the cut off value of 15%, inducing some spurious time variability that is not present in the computation of ice area. Nevertheless, the conclusions derived below for the ice area are qualitatively similar for the ice extent.

The spatial distribution of the ice concentration simulated by the model is in relatively good agreement with satellite observations (Figure 2) and is certainly well in the range of the results of the other climate

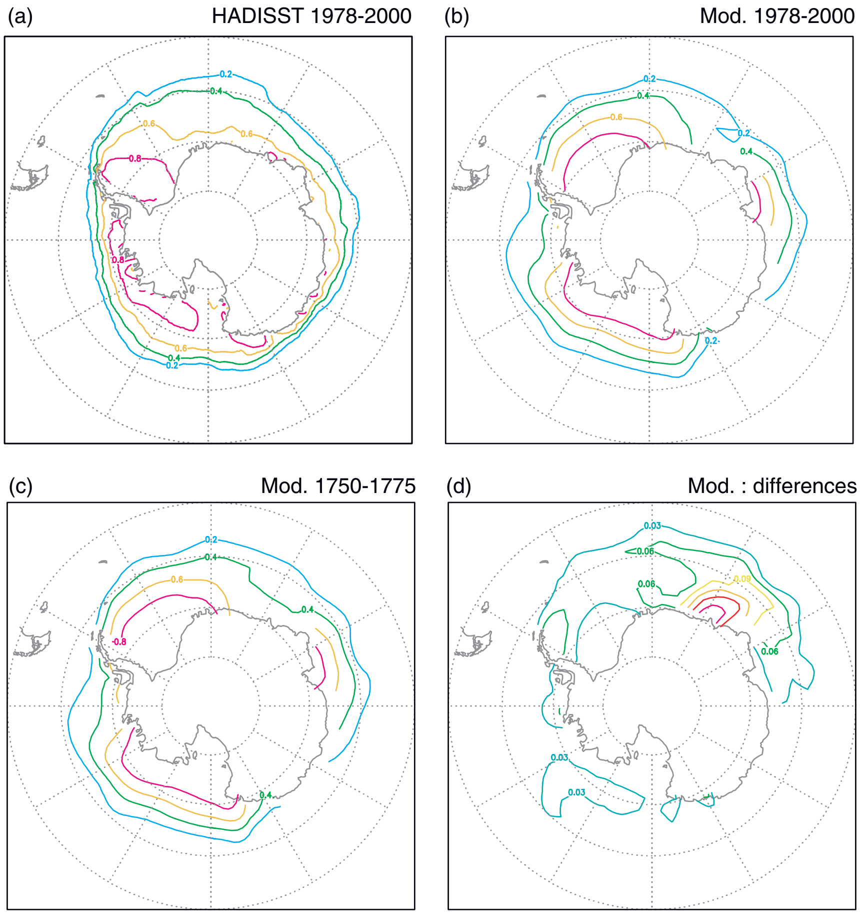

Figure 2. Annual mean ice concentration in the Southern Ocean. (a) HADISST1 data set (Rayner *et al*., 2003) averaged over the period 1978–2000. (b) Model results averaged over the ensemble of simulations for the period 1978–2000. (c) Ensemble mean averaged over the period 1750–75, which corresponds to the maximum over the last millennium. (d) Difference in annual mean ice concentration in the ensemble mean between 1750–75 and 1978–2000. Contour interval is 0.2 for (a), (b) and (c) and 0.03 for (d). This figure is available in colour online at http://www.interscience.wiley.com/ijoc

models (for more information, see Flato (2004)). Maximum ice extent occurs in the Weddell and Ross Seas, as expected. Furthermore, they are the only regions where ice is present in summer. The model underestimates the ice cover off the Adélie Coast, where the ice edge is relatively close to the coast and is thus difficult to represent at our resolution. On the other hand, the model overestimates the ice area in the Bellingshausen Sea. Overall, this results in a total ice area that is too high compared with observations (see Figure 1). The overestimation of the ice area in the Bellingshausen Sea occurs only in winter and is due to the Antarctic Circumpolar Current (ACC) being located too far to the north. This results in a too small oceanic heat flux in the model in this area, which is not able to restrain ice formation. Averaged over the whole Southern Ocean, this oceanic heat flux is reasonable, with a value of about 20 W/m^2 (Goosse and Renssen, 2001). The simulated interannual variability of the ice cover is also in relatively good agreement with observations, the dominant mode being related to SAM. The standard deviation of the annual mean ice area for the period 1978–2000 has a value of 0.2×10^6 km^2 for the ensemble mean and between 0.3×10^6 km^2 and 0.4×10^6 km^2 for the individual simulations. This is higher than the value deduced for HADISST1 for the same period (0.2×10^6 km^2), which corresponds to the one for which we have the most reliable data. Nevertheless, for the period 1970–2000, this standard deviation reached 0.4×10^6 km^2 for HADISST1 because of the large peak in the early 1970s.

3. SIMULATING THE PAST VARIATION OF THE ICE COVER IN THE SOUTHERN OCEAN

Over the last 150 years, the ensemble mean annual ice area for the 10 simulations displays a negative trend of 0.05×10^6 km^2/10years, i.e. about 0.75×10^6 km^2 (7%) over this period (Figure 1(a)). This decrease takes place during the whole period and appears only marginally stronger for the last 50 years (0.07×10^6 km^2/10years). It occurs all year long, but is weaker in winter with a decrease of only 3% over the last 150 years.

A decrease of 7% is smaller than the value reported by Rayner *et al*. (2003), who obtained a value of 11% over the same period (Figure 1(a)), but we must recall that large uncertainties exist in the observations of the ice area before the 1970s. Other models also simulate a decrease during the 20th century (e.g. Wu *et al*., 1999; Flato and Boer, 2001; Gregory *et al*., 2002), our value being on the low side compared with the other models. This could be due to a lower sensitivity of our model or to a different experimental design, as discussed below.

The ensemble mean provides a measure of the response of the system to the forcing, and the spread of the various ensemble members around this forced response can be used to estimate the natural variability. The ensemble range is defined here as the ensemble mean plus and minus one standard deviation of the ice area simulated in the 10 members of the ensemble each year. This standard deviation is thus different each year. Hereafter, it will be referred to as the standard deviation of the ensemble.

When data are grouped in decadal averages in order to filter the high-frequency variations, the standard deviation of the ensemble reaches 0.35×10^6 km^2 at the end of the simulation (Figure 1(b)). As a consequence, a decreasing trend of 0.07×10^6 km^2/10years as simulated by the model would correspond to 0.18×10^6 km^2, half the standard deviation of the ensemble, over the period 1978–2002 for which we have the most reliable data. This means the decreasing trend could not be detected using 25 years of data, in agreement with the conclusions of Flato and Boer (2001). If this trend remains constant in the future, then 25 additional years would be necessary to have a forced decrease reaching one standard deviation of the ensemble and, thus, a reasonably good chance to record the long-term decrease using such a satellite-based record.

If the time series is extended back to 1972 following Cavalieri *et al*. (2003), then the observed trend is much larger. Nevertheless, the large decrease is entirely due to changes during the 1970s and, thus, appears more related to a high-frequency anomaly during this period rather than to a long-term trend. On the other hand, the long-term decreases of Rayner *et al*. (2003) and Curran *et al*. (2003) are clearly not compatible with the internal variability simulated by the model. If those time series represent unbiased measures of the past variation of the ice cover, then this trend should thus be due to the response to an external forcing according to our results.

It must be stressed that the results presented above must be treated with caution because they are based on simulated trends and internal variability, both of which are largely uncertain. In particular, the internal variability of the model is higher than the variability observed during the last 20 years and the trend is in the low range of climate model results. Furthermore, the trend could change in the future. The proposed record length of 40 to 50 years to have a reasonable estimate of long-term trends must thus be considered as providing only an order of magnitude at this stage.

In our simulations, the decrease of the ice area during the last 150 years is part of a long-term decline that started in the mid 18th century when the annual mean ice area was roughly 1×10^6 km^2 higher than now. The majority of the changes are in the Weddell Sea, in particular in the eastern part, and to a smaller extent in the Ross Sea. This long-term decreasing trend is present in all the members of the ensemble.

The minimum over the pre-industrial period occurred during the years AD 1250–1500. This agrees with the hypothesis of Goosse *et al*. (2004), that the sea-surface temperature in the Southern Ocean lags the conditions in the Northern Hemisphere, where the simulated temperatures reach a maximum in the model during the 11 and 12th centuries (Goosse *et al*., 2004; Goosse and Renssen, 2004). Such a lag is due to the long memory of the ocean associated with the storage and transport of temperature anomalies at great depth (Goosse *et al*., 2004). Between AD 1250 and 1500 the simulated Antarctic ice area was similar to that at the end of the 20th century. This shows that, despite the large decrease in ice area simulated during the last 250 years, the ice area at the end of the 20th century could not be considered as unprecedented during the last 1000 years in our simulations.

This result contrasts with the surface air temperature averaged over the Northern Hemisphere, which is higher at the end of the 20th century than at any other time during the second millennium, both in observations (Mann *et al.*, 1999; Houghton *et al.*, 2001) and in the model (Goosse *et al.*, 2004). It also contrasts with the variations of the surface temperature and ice area in the Arctic simulated by the model (Goosse and Renssen, 2003), which at the end of the 20th century reach their absolute maximum and minimum respectively. In addition, the surface air temperature averaged over the Southern Hemisphere also displays values in the model that are higher at the end of the 20th century than during any period of the millennium. This is in agreement with the observations (e.g. Mann and Jones, 2003; Goosse *et al.*, 2004), although those reconstructions are less reliable than in the Northern Hemisphere (Andronova *et al.*, 2004; Mann and Jones, 2003).

The peculiar behaviour of the Southern Ocean is due to its delayed response to any external radiative forcing, as shown for instance by Weaver *et al.* (2000) and Goosse and Renssen (2001). In particular, the latter study compares two experiments: a transient experiment similar to the one presented here and a long simulation using constant, present-day (i.e. AD 2000) forcing in which the simulated climate reached a steady state. They have shown that the equilibrium value for the Antarctic ice area reached at the end of this long experiment is 4×10^6 km^2 lower than the value simulated in AD 2000 in the transient experiment. As a consequence, the ice area at steady state, using the external forcing observed in AD 2000, would be much smaller than the value simulated during the pre-industrial period, even for the years AD 1250–1500. However, the transient value of the Antarctic ice area observed in 2000 is still far away from this steady state and thus not unprecedented in the second millennium.

This raises the question of whether the forced decline in the ice area simulated during the 20th century is due to a slow recovery from the cold conditions at the end of the 18th century or whether it is linked to anthropogenic activity. In order to provide information on this important topic, an ensemble of five simulations has been performed using natural (solar and volcanic) forcings only, starting in AD 1750. During the 18th and 19th centuries, the two types of simulation are nearly identical (Figure 3), but during the 20th century the ensemble mean of the ice area is clearly higher in the simulation using only natural forcing. Over the last 150 years (50 years), the negative trend in the simulation using natural forcing only is 0.01×10^6 km^2/10 years (0.03×10^6 km^2/10 years), about five (two) times less than in the simulation using all the forcings.

These experiments show that the decline of the ensemble mean during the last 150 years in the simulations using all the forcings, which is a measure of the forced response of the climate system, is to a large extent due to anthropogenic activity according to our results. Nevertheless, because of the large uncertainties in

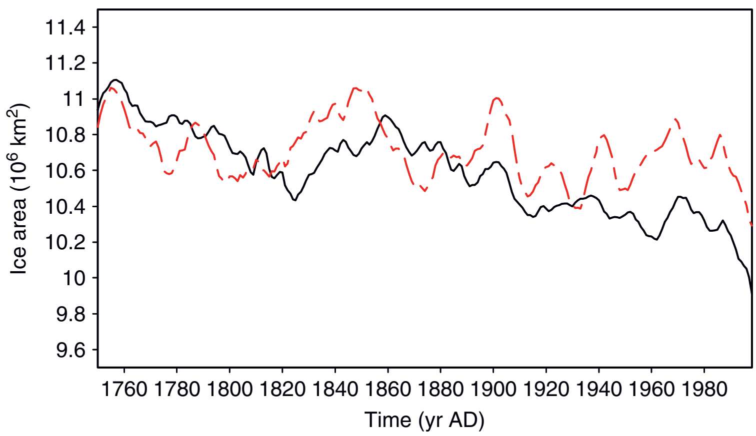

Figure 3. Ensemble mean of the annual mean ice area in the Southern Hemisphere during the last 250 years using both anthropogenic and natural forcings (black solid) and natural forcing only (dashed). A 10-year running mean has been applied to the time series. This figure is available in colour online at http://www.interscience.wiley.com/ijoc

the available proxy-based reconstructions, it is presently not possible to state which one of the two sets of experiments is in better agreement with observations.

4. ROLE OF THE LONG MEMORY OF THE OCEAN

Because of the large computer-time requirements of models, it is not always possible to perform a very long spin-up before starting an experiment with an AOGCM. Nevertheless, it is generally considered that starting a simulation devoted to analysing climate in the 20th and 21st centuries from a state representative of the pre-industrial climate (for instance 1850) allows problems related to initial conditions to be minimized (Fichefet and Tricot, 1992; Cubasch *et al*., 1995; Keen and Murphy, 1997). This appears to be valid for a large part of the world, but it may not be for the Southern Ocean because of the delayed response of the climate system at those latitudes, even at the surface.

This could be illustrated by showing the time variation of the standard deviation of the annual mean ice area as simulated in the ensemble of simulations using all the forcings, i.e. the range displayed in Figure 1 (Figure 4(a)). In the Northern Hemisphere, the standard deviation of the 10 simulations is relatively constant during the 1000-year period and appears only weakly influenced by initial conditions. In the Southern Hemisphere, however, this standard deviation is up to two times higher during the first 200 years of the simulation compared with the values at the end of the experiments. This highlights the role of the long memory of the ocean for the Southern Ocean and shows that initial conditions could have a long-term influence on any simulation of the variation of the ice area in this region.

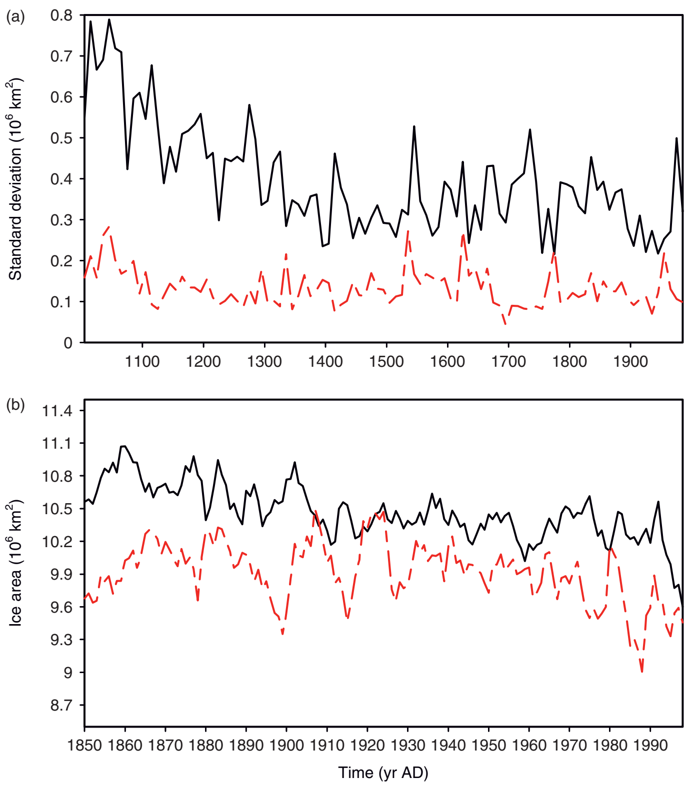

Figure 4. (a) Time series of the standard deviation over the 10 simulations of the annual mean ice area in the Southern Hemisphere (black solid) and in the Northern Hemisphere (dashed) for the last 1000 years. (b) Annual mean ice area in the Southern Hemisphere during the last 150 years averaged over 10 simulations starting in AD 1000 (black solid) and five simulations starting in AD 1850 (dashed). This figure is available in colour online at http://www.interscience.wiley.com/ijoc

In order to have a more direct comparison of the ice area obtained in our simulations covering the whole millennium with the experiments performed with AOGCMs starting in 1850, we have conducted an additional ensemble of five experiments starting from an equilibrium state corresponding to pre-industrial conditions (i.e. AD 1850). These experiments were started with a less extensive sea ice area (Figure 4(b)) than in the transient simulations over the last 1000 years at the same date, the value in AD 1850 in the latter group of experiments being close to the maximum for the last millennium. In these new experiments, the ice area first increases until AD 1920 and then decreases. Nevertheless, the ensemble mean ice area mostly remains below the mean of the experiments started in AD 1000. Because of the increase in ice area between 1850 and 1920, the trend over the last 150 years simulated in the experiment starting in AD 1850 (-0.03×10^6 km^2/10 years) is less than in the standard experiment. Besides the trend is higher than in the standard experiment for the last 50 years (-0.11×10^6 km^2/10 years).

5. CONCLUSIONS

The main conclusions of this study are as follows:

1. The variation of the ice area in the Southern Hemisphere displays a decreasing trend of about 0.04 km^2/10 years during the last 250 years in our simulations. This is consistent with previous modelling studies analysing the variation during the 20th century. This trend is too small to be detected by the satellite observations covering the last 25 years, and about 50 years of observations would be necessary to have a reasonable estimate on the long-term trend of the ice area, according to our results. On the other hand, this long-term decrease agrees reasonably well with the results of Rayner *et al.* (2003) and Curran *et al.* (2003). Nevertheless, as those time series are based on a small number of observations, they bear large uncertainties.
2. The modelling experiments indicate that the decline of the ice area during the last 250 years is driven by both natural and anthropogenic forcings. For the ensemble mean of our simulations, the respective contributions in the trends over the last 250 years of the natural and anthropogenic forcings are roughly similar, whereas over the last 150 years the latter induce a trend that is about five times stronger than that due to natural forcing alone. Despite this role of anthropogenic forcing, the sea ice cover at the end of the 20th century does not appear as anomalous compared with the variation during the last millennium in our simulation. This is due to a delayed response of the Southern Ocean to the anthropogenic forcing. Therefore, further reductions in ice area can be expected in this century (e.g. Flato and Boer, 2001; Goosse and Renssen, 2001; Houghton *et al*., 2001, Flato, 2004).
3. The delayed response of the Southern Ocean and the long memory of the deep ocean water masses are crucial for the design of numerical experiments. It takes more than 200 years for the influence of initial conditions to disappear at the surface of the Southern Ocean, i.e. a much longer time scale than in other regions. For instance, if numerical experiments are started in AD 1850 from an equilibrium state, then the ice area will be underestimated in our model during the whole 20th century compared with experiments started in AD 1000. The initial conditions could also have an impact on the magnitude of the negative trend simulated during the 20th century.

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REFERENCES

Ackley S, Wadhams P, Comiso JC, Worby AP. 2003. Decadal decrease of Antarctic sea ice extent inferred from whaling records revisited on the basis of historical and modern sea ice records. *Polar Research* **22**: 19–25.

Andronova NG, Schlesinger ME, Mann ME. 2004. Are reconstructed pre-industrial hemisphere temperatures consistent with instrumental hemispheric temperatures? *Geophysical Research Letters* **31**: L12202. DOI: 1029/2004GL019658.

Bard E, Raisbeck G, You F, Jouzel J. 2000. Solar irradiance during the last 1200 years based on cosmogenic nuclides. *Tellus, Series B: Chemical and Physical Meteorology* **52**: 985–992.

Bi DH, Budd WF, Hirst AC, Wu XR. 2001. Collapse and reorganisation of the Southern Ocean overturning under global warming in a coupled model. *Geophysical Research Letters* **28**(20): 3927–3930.

Cavalieri DJ, Parkinson CL, Vinnikov KY. 2003. 30-year satellite record reveals contrasting Arctic and Antarctic decadal sea ice variability. *Geophysical Research Letters* **30**(18): 1970. DOI: 10.1029/2003GL018931.

Comiso JC. 2000. Variability and trends in Antarctic surface temperatures from *in situ* and satellite infrared measurements. *Journal of Climate* **13**: 1674–1696.

Crowley TJ. 2000. Causes of climate change over the past 1000 years. *Science* **289**: 270–277.

Cubasch U, Hegerl GC, Hellbach A, Höck H, Mikolajewicz U, Santer BD, Voss R. 1995. A climate change simulation starting from 1935. *Climate Dynamics* **11**: 71–84.

Curran M, van Ommen TD, Morgan VI, Phillips KL, Palmer AS. 2003. Ice core evidence for Antarctic sea ice decline since the 1950s. *Science* **232**: 1203–1206.

De la Mare WK. 1997. Abrupt mid-twentieth-century decline in Antarctic sea-ice extent from whaling records. *Nature* **389**: 57–60.

Doran PT, Priscu JC, Lyons WB, Walsh JE, Fountain AG, McKnight DM, Moorhead DL, Virginia RA, Wall DH, Clow GD, Fritsen CH, McKay CP, Parsons AN. 2002. Antarctic climate cooling and terrestrial ecosystem response. *Nature* **415**(6871): 517–520.

Fichefet T, Tricot C. 1992. Influence of the starting date of model integration on projections of greenhouse-gas-induced climatic change. *Geophysical. Research Letters* **19**(17): 1771–1774.

Fichefet T, Tartinville B, Goosse H. 2003. Antarctic sea ice variability during 1958–1999: a simulation with a global ice–ocean model. *Journal of Geophysical Research* **108**(C3): 3102. DOI: 10.1029/2001JC001148.

Flato GM. 2004. Sea-ice and its response to CO_2 forcing as simulated by global climate models. *Climate Dynamics* **23**: 229–241.

Flato GM, Boer GJ. 2001. Warming asymetry in climate change simulations. *Geophysical Research Letters* **28**(1): 195–198.

Goosse H, Fichefet T. 1999. Importance of ice–ocean interactions for the global ocean circulation: a model study. *Journal of Geophysical Research* **104**(C10): 23 337–23 355.

Goosse H, Renssen H. 2001. A two-phase response of Southern Ocean to an increase in greenhouse gas concentrations. *Geophysical Research Letters* **28**: 3469–3473.

Goosse H, Renssen H. 2003. Simulating the variation of the Arctic climate during the last millennium. In *7th AMS Conference on Polar Meteorology and Oceanography*, 1.5. http://www.astr.ucl.ac.be/users/hgs/ams_arctic.pdf.

Goosse H, Renssen H. 2004. Exciting natural modes of variability by solar and volcanic forcing: idealized and realistic experiments. *Climate Dynamics* **23**: 153–163.

Goosse H, Selten FM, Haarsma RJ, Opsteegh JD. 2002. A mechanism of decadal variability of the sea-ice volume in the Northern Hemisphere. *Climate Dynamics* **19**: 61–83.

Goosse H, Masson-Delmotte V, Renssen H, Delmotte M, Fichefet T, Morgan V, van Ommen T, Khim BK, Stenni B. 2004. A late medieval warm period in the Southern Hemisphere as delayed response to external forcing? *Geophysical Research Letters* **31**(6): L06203. DOI: 10.1029/2003GL019140.

Gregory JM, Stott PA, Cresswell DJ, Rayner NA, Gordon C, Sexton DMH. 2002. Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM. *Geophysical. Research Letters* **29**(24): 2175. DOI: 10.1029/2001GL14575.

Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA. 2001. Climate Change 2001. *The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK.

Johannessen OM, Bengtsson L, Miles MW, Kuzmina SI, Semenov VA, Alekseev GV, Nagurnyi AP, Zakharov VF, Bobylev L, Pettersson LH, Hasselmann K, Cattle HP. 2004. Arctic climate change — observed and modeled temperature and sea ice variability. *Tellus, Series A: Dynamic Meteorology and Oceanography* **56**: 328–341.

Jones JM, Widmann M. 2003. Instrument- and tree-ring based estimates of the Antarctic oscillation. *Journal of Climate* **16**: 3511–3524.

Jones PD. 1990. Antarctic temperatures over the present century — a study of the early expedition record. *Journal of Climate* **3**: 1193–1203.

Keen AB, Murphy JM. 1997. Influence of natural variability and the cold start problem on the simulated transient response to increasing CO_2. *Climate. Dynamics* **13**: 847–864.

Kwok R, Comiso JC. 2002. Southern Ocean climate and sea ice anomalies associated with the southern oscillation. *Journal of Climate* **15**: 487–501.

Lean J, Beer J, Bradley R. 1995. Reconstruction of solar irradiance since 1610: implications for climate change. *Geophysical. Research Letters* **22**: 1591–1594.

Lefebvre W, Goosse H, Timmermann R, Fichefet T. 2004. Influence of the southern annular mode on the sea-ice–ocean system. *Journal of Geophysical Research* **109**: C090005. DOI: 10.1029/2004JC002403.

Liu J, Curry JA, Martinson DG. 2004. Interpretation of recent Antarctic sea ice variability. *Geophysical Research Letter* **31**: L02205. DOI: 10.1029/2003GL018732.

Manabe S, Stouffer RJ, Spelman MJ, Bryan K. 1991. Transient responses of a coupled atmosphere–ocean model to gradual changes of atmospheric CO_2. I. Annual mean response. *Journal of Climate* **4**: 785–818.

Mann ME, Jones PD. 2003. Global surface temperatures over the past two millennia. *Geophysical Research Letters* **30**(15): 1820. DOI: 10.1029/2003GL017814.

Mann ME, Bradley RS, Hughes MK. 1999. Northern Hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical. Research Letters* **26**: 759–762.

Marshall GJ. 2003. Trends in Antarctic geopotential height and temperature: a comparison between radiosonde and NCEP–NCAR reanalysis data. *Journal of Climate* **15**: 659–674.

Morgan VI. 1985. An oxygen isotope–climate record from the Law Dome, Antarctica. *Climatic Change* **7**: 415–426.

Opsteegh JD, Haarsma RJ, Selten FM, Kattenberg A. 1998. ECBILT: a dynamic alternative to mixed boundary conditions in ocean models. *Tellus, Series A: Dynamic Meteorology and Oceanography* **50**: 348–367.

Parkinson CL. 1990. Search for Little Ice Age in Southern Ocean sea-ice records. *Annals of Glaciology* **14**: 221–225.

Parkinson CL, Cavalieri DJ, Gloersen P, Zwally HJ, Comiso JC. 1999. Arctic sea ice extents, areas and trends, 1978–1996. *Journal of Geophysical Research* **97**: 17 715–17 728.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of sea surface temperature, sea ice, and nigh marine air temperature since the late nineteenth century. *Journal of Geophysical Research* **108**(D14): 4407. DOI: 10.1029/2002JD002670.

Stenni B, Proposito M, Gragnani R, Flora O, Jouzel J, Falourd S, Frezzotti M. 2002. Eight centuries of volcanic signal and climate change at Talos Dome (East Antarctica). *Journal of Geophysical Research* **107**(D9): 4076. DOI: 10.1029/2000JD000317.

Stouffer RJ, Manabe S, Bryan K. 1989. Interhemispheric assymmetry in climate response to a gradual increase of atmospheric CO_2. *Nature* **342**: 660–662.

Turner J, King JC, Lachlan-Cope TA, Jones PD. 2002. Recent temperature trends in the Antarctic. *Nature* **418**: 291–292.

Turner J, Colwell SR, Marshall GJ, Lachlan-Cope TA, Carleton AM, Jones PD, Lagun V, Reid PA, Iagovkina S. 2004. The SCAR READER project: toward a high-quality database of mean Antarctic meteorological observations. *Journal of Climate* **17**: 2890–2898.

Vaughan DG, Marshall GJ, Connolley WM, Parkinson C, Mulvaney R, Hodgson DA, King JC, Pudsey CJ, Turner J. 2003. Recent rapid regional climate warming on the Antarctic Peninsula. *Climatic Change* **60**: 243–274.

Vinnikov KY, Robock A, Stouffer RJ, Walsh JE, Parkinson CL, Cavalieri DJ, Mitchell JFB, Garrett D, Zakharov VF. 1999. Global warming and Northern Hemisphere sea ice extent. *Science* **286**: 1934–1937.

Watkins AB, Simmonds I. 2000. Current trends in Antarctic sea ice: the 1990s impact on a short climatology. *Journal of Climate* **13**: 4441–4451.

Weaver AJ, Duffy PD, Eby M, Wiebe EC. 2000. Evaluation of ocean and climate models using present-day observations and forcing. *Atmosphere Ocean* **38**: 271–301.

Wu XR, Budd WF, Jacka TH. 1999. Simulations of Southern Hemisphere warming and Antarctic sea-ice changes using global climate models. *Annals of Glaciology* **29**: 61–65.

Zwally HJ, Parkinson CL, Comiso JC. 1983. Variability of Antarctic sea ice and changes in carbon dioxide. *Science* **220**: 1005–1012.

Zwally HJ, Comiso JC, Parkinson CL, Cavalieri D, Gloersen P. 2002. Variability of Antarctic sea ice 1979–1998. *Journal Geophysical Research* **107**(C5): DOI: 10.1029/2000JC000733.

